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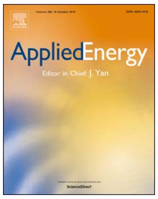

Assessing the effectiveness of a global optimum strategy within a tidal farm for power maximization

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HIGHLIGHTS

- We assess the effectiveness of a global optimum strategy in tidal farms.
- The power is maximized by determining the operating point of each tidal turbine.
- The stronger is the flow interactions between devices, the more efficient is the strategy.
- Applying the strategy to the Alderney race, the mean power increases by 0.87%.

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ABSTRACT

In the next years, tidal farm will increase in size and density of devices to obtain an economically significant amount of energy. Because of the high density of the devices within the farm, the turbines will be hydrodynamically coupled. The negative effects of this coupling could be reduced by optimizing the tidal farm layout or by optimizing the operating point of each turbine within the farm. In this paper, we investigate the second strategy. The objective is to maximize the overall production of the farm. The power of the upstream tidal turbines is then reduced, allowing the increase of power of the downstream turbines. The Binary Particle Swarm Optimization (BPSO) Algorithm is used in order to find the rotational speed for each device such that the net energy yield is optimized over a tidal cycle.

The proposed methodology is firstly applied to an ideal case (i.e. tidal flow constant in magnitude and direction) to assess the influence of the machines density, the ambient turbulence rate and the speed magnitude on the power improvement rate. Secondly, the method is applied to a hypothetical tidal farm located in the Alderney Race (Raz Blanchard in French), situated between the Alderney Island and La Hague Cape (France). The results of these scenarios indicate that the proposed strategy is interesting mainly when the density of devices is high and/or when the ambient turbulence rate is lower than 10%. In this cases, it is possible to improve the rate by 2.5%.

1. Introduction

The need to diversify the energy mix in Europe encourages the global community to search alternative energy resources in order to reduce the degradation of the environment [1]. Marine Renewable Energies (MREs) have thus drawn the attention of industrials and researchers. Among MREs (thermal energy, chemical energy, biological energy and kinetic energy), the tidal current energy seems to be the most interesting [2]. It has the advantage of being highly predictable, requiring limited land occupation and having a limited visual impact. The processes involved in the conversion of tidal energy are the extraction of kinetic energy from tidal currents, the conversion into mechanical energy (using a tidal turbine), and the conversion into electrical energy (through electrical generators). Given the small surface of sites suitable for tidal energy extraction (few km^2), a large number of turbines should be installed to harness the maximum power of a site. However, a high density of turbines implies significant flow interactions between the turbines' wakes. When several turbines are aligned with the upstream current, the downstream turbines extract less power than the ones located upstream, which reduces significantly the energy produced by a tidal farm [3]. Increasing the longitudinal distance between the tidal devices permits to reduce the negative effects of the flow interactions. However, the maximal distance is constrained by the surface availability and the cost of electrical connections. Two

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alternative ways to reduce the wake effects could thus be followed: optimizing the tidal farm layout configuration or optimizing the operating point of each turbine in the tidal farm.

The first approach (layout optimization) has been investigated in recent papers. Funke et al. [4] optimized the placement of turbines combining a bi-dimensional flow model with a gradient optimization algorithm. Their method allowed them to increase the power production by 33% compared to a classic aligned configuration. Stansby and Stallard [5] optimized the turbine arrangements of little tidal farms (two or three rows of devices) in shallow waters using a semi-analytical wake model developed from measurements of a single wake [6] and validated for small arrays with the experimental data of Olczak et al. [7]. Lo Brutto et al. [8] used a semi-analytical method to optimize the layout of tidal turbines with small diameter to depth ratio. They used a Particle Swarm Optimization (PSO) algorithm coupled to an analytical model developed in Lo Brutto et al. [9] to represent the interaction between the wakes of the turbines. The authors cited earlier worked in flat bed, so that bathymetric variations were neglected. The aforementioned studies indicate that optimized layouts are generally not symmetric. However, it is more probable that tidal farm developers will prefer using regular layout to facilitate the installation and maintenance operations.

Considering a given layout, the negative wake effects can be minimized with an improved power maximization strategy within the farm. Several recent papers [10–14] are dedicated to the maximization of the power produced by a single turbine, the so-called *Self-Optimum Strategy* (*SOS*, [15]). However, at the farm scale, it is not guaranteed that the SOS is the optimum choice for the overall power production. This is due to the fact that the energy captured by each tidal device reduces the hydrodynamic power available to the turbines located downstream. This makes the maximization of a tidal farm power challenging. Two methods can be used to control the wakes' interactions in a tidal farm: redirecting the wakes by yaw control [16] and reducing wake interaction by adjusting the axial induction [17]. The second method consists in reducing the power generated by the turbines located upstream in order to limit the velocity reduction and the wake effect losses. By doing so, a greater power is available for the downstream turbines. As the energy extraction is distributed more uniformly over the farm, the total production of the tidal farm is improved [18]. This approach is known in the literature as *Global Optimum Strategy (GOS)*. As far as we know, only Hunter et al. [19] tuned tidal turbines in order to increase the power of a row of tidal turbines (four and eight turbines arrays). The effect of tuning non-uniformly the tidal turbines was analyzed in repeated simulations where different values of the thrust coefficient were tested. They found that a non-uniform thrust coefficient across the array allows an increase of the power produced by the farm, and that a uniform tuning of the thrust coefficient results in a non-uniform distribution of the power. This strategy was not extended to an optimization method because of the high computational costs of their Computational Fluid Dynamics (CFD) model. Studies of GOS are more advanced in wind farm applications. They generally rely on the coupling between an optimization algorithm for finding the best operating points of the turbines, and a simple model to represent the wakes and their interactions. The first authors who proposed a GOS of a wind farm are Steinbuch et al. [20]. Through a trial and error method, they selected the Tip Speed Ratio (TSR) of each wind turbine defined as:

$$\mathrm{TSR} = \lambda = \frac{\omega_r \cdot r_0}{U_0} \tag{1}$$

where ω_r is the rotational speed of the turbine, r_0 is the turbine radius and U_0 is the wind speed. They concluded that what was gained with their method was not significant. On the contrary, some authors demonstrated experimentally the effectiveness of using a GOS in wind farms application. Corten and Schaak [21] performed a wind tunnel test using 3 × 8 turbines under constant wind speed and direction. They demonstrated that the optimized control strategy (changing the blade angle of the first row of turbines) increases the total farm power by 4.6%. Corten et al. [22] showed that it is possible to improve the generated power of a farm by changing the TSR of each device. Adaramola and Krogstad [23] have shown with experiments in wind tunnels on two turbines that decreasing the power extraction of the first turbine allows an increase of the overall production of the two devices of about 12%. In their technical report, Larsen et al. [24] presented the TOPFARM project, which concerned the optimization of the control strategy within a farm. Although the way they achieved that improvement was not reported in the paper, the authors underlined that it is possible to increase the overall production of a park by changing the operating point of each turbine. Full scale field tests were performed by Machielse et al. [25], which analyzed the improvement achieved by a GOS using five pitch controlled 2.5 MW turbines. The authors obtained an increase in power production of 0.5%. Schepers and Van der Pijl [26] showed – through the measurement results from the Energy Research Centre of the Netherlands (ECN) research farm – the benefits of changing the operating point of each turbine in a farm.

The experimental validation of the GOS achieved by the aforementioned authors was the starting point of studies, where the GOS was applied to improve the power production of a farm though optimization algorithms. As an example, Lee et al. [27] controlled the pitch angles of turbines to increase the output of a wind farm. They applied their method using the wind farm of Horns Rev (Denmark) as a reference, keeping the same relative distances (7D in both longitudinal and transverse directions). Genetic Algorithm (GA) was used to optimize the total aerodynamic power output of the wind farm. They demonstrated that optimizing the pitch variation of the turbines increases the power generated by Horns Rev by 4.5%. These results were improved by Serrano-González et al. [28]. Similarly to [27], they used the layout configuration of the Horns Rev wind farm as a reference. GA was chosen as a tool for maximizing the overall power output of the wind farm, as a function of the TSR and of the pitch angle of each wind turbine. They demonstrated that the method is promising as it gives a greater production than the one obtained with the SOS. De-Prada-Gil et al. [29] proposed another methodology consisting in optimizing the TSR of each turbine. By modulating spatially the energy extraction, the wake effects within the wind power plant are reduced and the overall power of the farm is increased. They applied their methodology to a 9 wind turbines farm laid out in a rectangular matrix of 3 rows and 3 columns. The spacing between wind turbines was 7 diameters D in the longitudinal direction (parallel to the main wind direction) and 5D in the transverse direction. They demonstrated that, depending on the wind rose at the farm location, the GOS can increase the overall production up to 6.24%. Wang et al. [15] used Genetic Algorithm (GA) to find the induction factor of each turbine to increase the overall production. Their results showed that the GOS enables an increase of the wind farm efficiency up to 1.4%. All the aforementioned studies indicate that in wind farms, there is generally a dominant flow direction, which makes the control strategy simpler. In tidal farm applications, the flow is bi-directional with more or less directional spreading. This difference makes the optimization strategy more challenging.

The aim of this paper is to assess the effectiveness of a GOS in tidal farm applications in order to increase the generated power. The power is maximized by determining the optimal TSR of each tidal turbine. Firstly, the methodology is applied to an ideal case (i.e. tidal flow constant in magnitude and direction) to assess the influence of the density of the machines, of the ambient turbulence rate and the speed magnitude on the power improvement rate. Secondly, the method is applied to a hypothetical tidal farm located in the Alderney Race (Raz Blanchard in French), situated between the Alderney Island and La Hague Cape (France).

The analytical model used to estimate the power produced by a tidal farm is presented in Section 2. The optimization problem is introduced in Section 3. Section 4 is dedicated to the description of the tested configurations. Finally, the results are presented in Section 5.